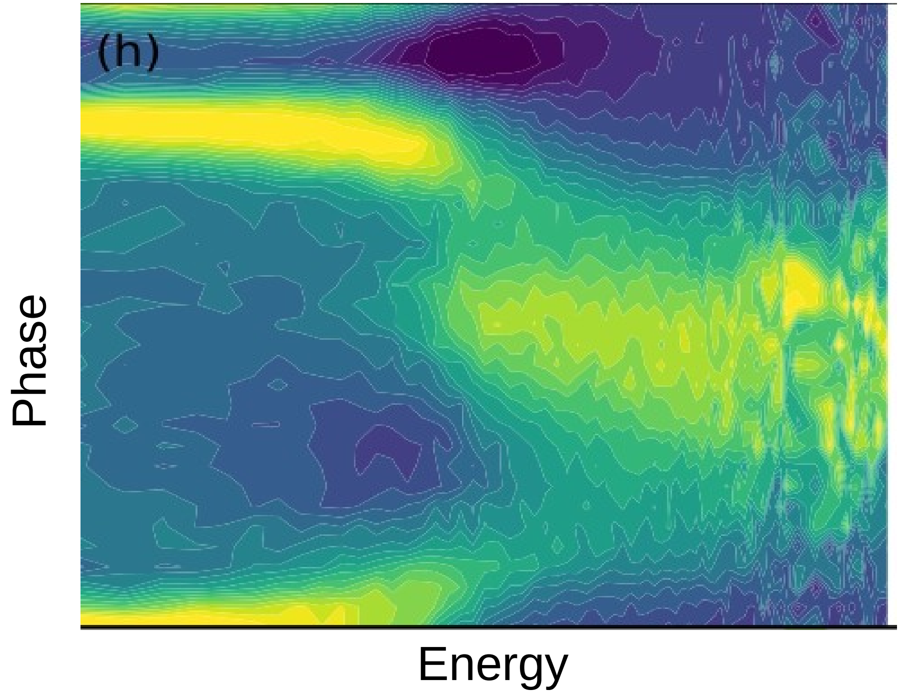
Investigating pulse profiles in magnetic high mass X-ray binaries



https://www.aanda.org/articles/aa/pdf/2023/09/aa47062-23.pdf

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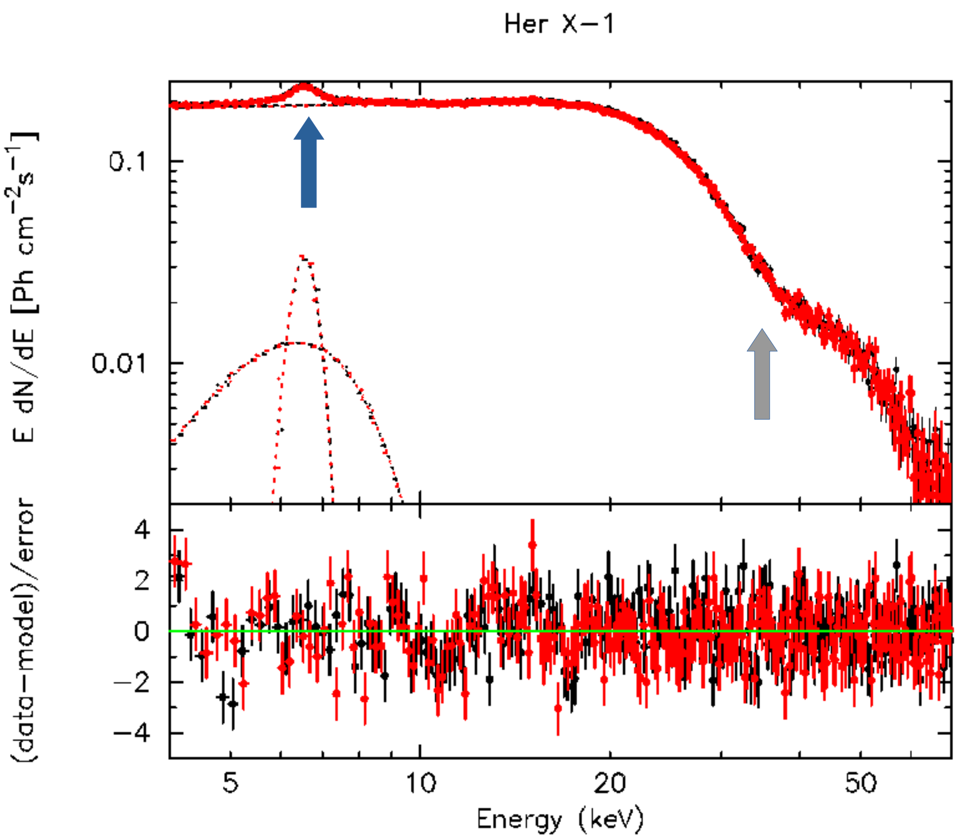
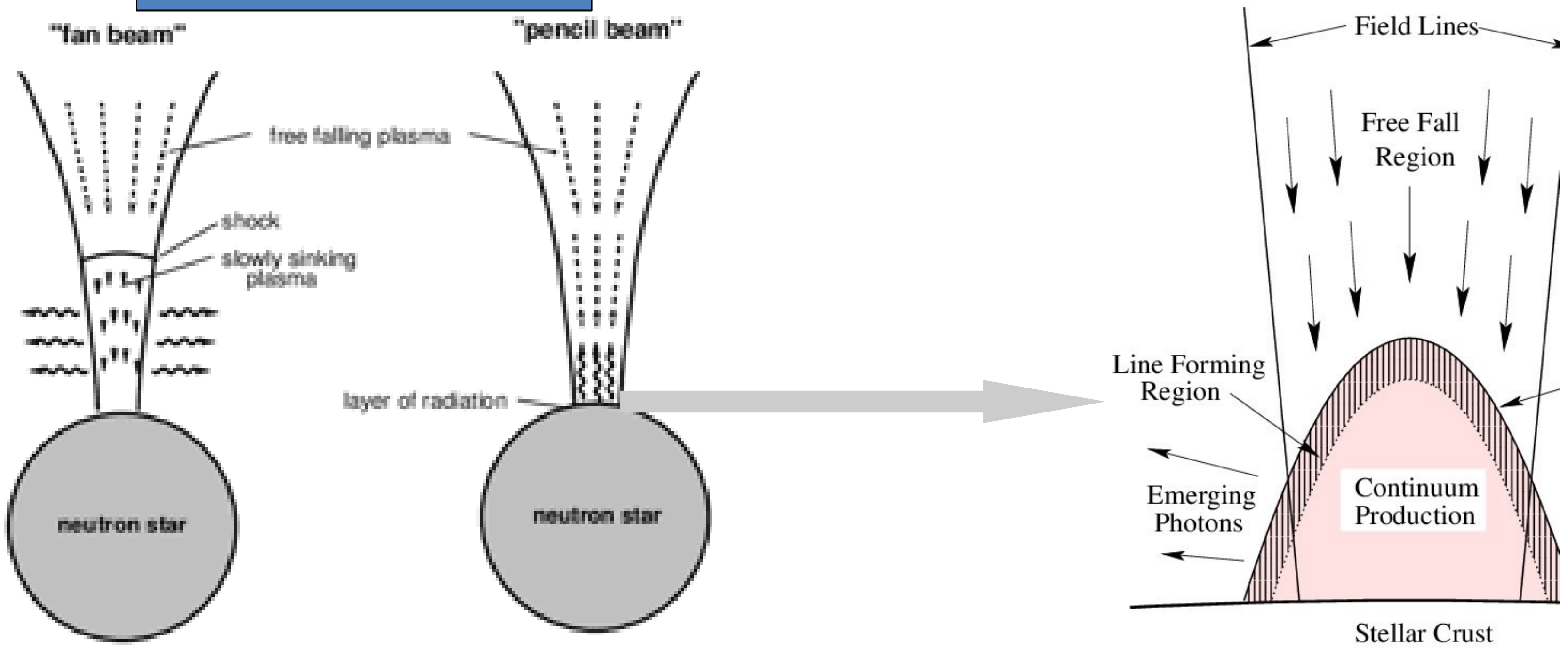
Emission model



- A power-law continuum with exponential cutoff at 15-20 keV to describe thermal Comptonization. However, are there multiple components ?
- An Iron fluorescence line complex (6.4 keV) originating in the wind of the donor or in the accretion flow.
- A cyclotron scattering feature above the cutoff (10-50 keV) which is due to the resonance scattering of electrons in the Landau levels.

Possible geometries

Isemberg et al. (1998)



The continuum emerges as fan or pencil beam for high and low luminosity.

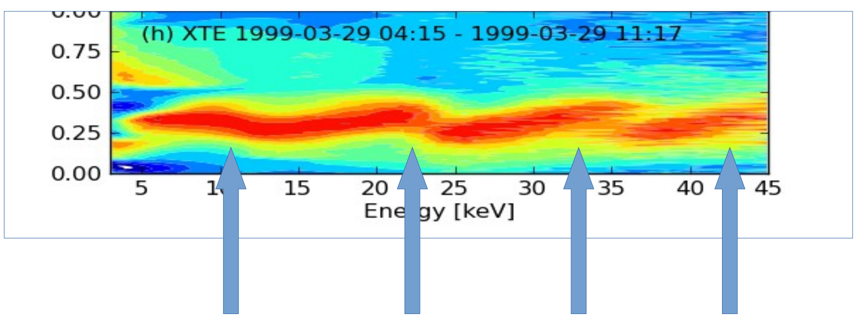
Cyclotron lines can be formed in the “photosphere” of the emission region.

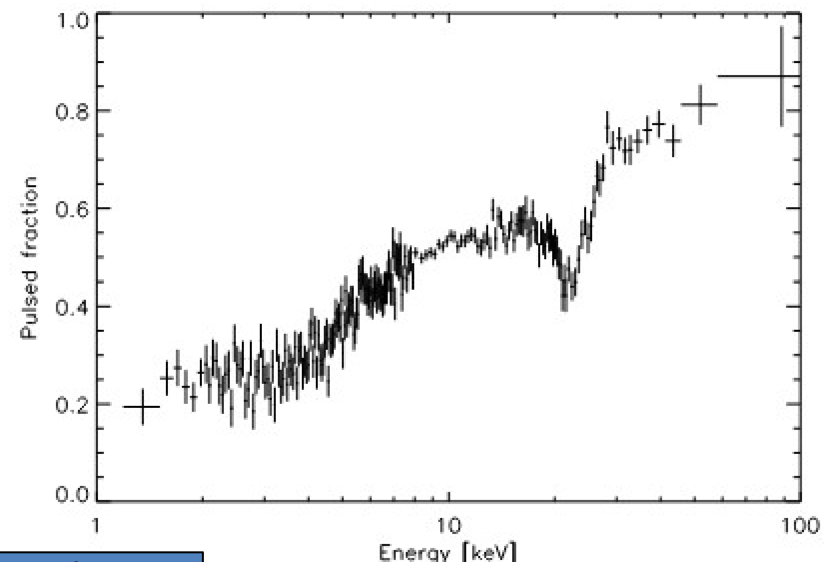
Uncertainties on the actual geometry, location of columns and their shape.

The starting point

Back in 2009, using BeppoSAX and RXTE data, we noticed in 4U 0115+63:

- a peculiar modulation of the pulse profiles in correspondence of the multiple cyclotron lines at 11, 22, 33, 44 keV.
- the pulsed fraction is energy dependent with features corresponding to cyclotron lines





Ferrigno et al. (2009,2011)

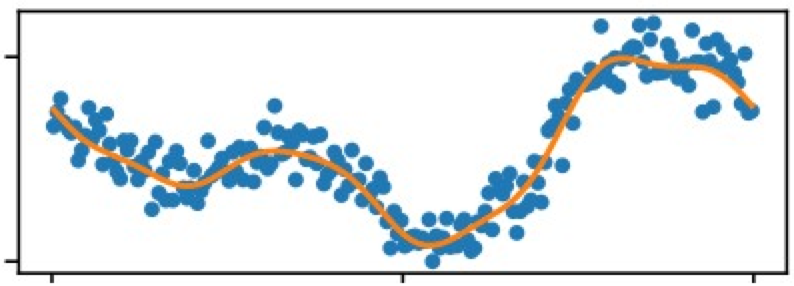
A systematic study

- We collected all observations of Cyclotron line sources in the NuSTAR archive
- We perform a uniform data reduction using standard and mostly automated processing
- The aim is to systematically compare the energy-dependent pulsed emission characteristics.
- Our pipelines optimizes the energy scale of pulse grid at a minimum S/N ratio. We provide exhaustive diagnostics from the energy dependent Fourier decomposition of pulse profiles.
- I present here a selection of intriguing sources.

Pulsed fraction determination

- We decompose each pulse in as many Fourier components necessary to describe the data at better than 90% c.f.
- We derive the total RMS as sum of the Fourier amplitudes and the relative uncertainty from a bootstrap simulation

$$RMS = \frac{1}{A_0}\sqrt{\sum_{k}^{n} A_k^2}$$



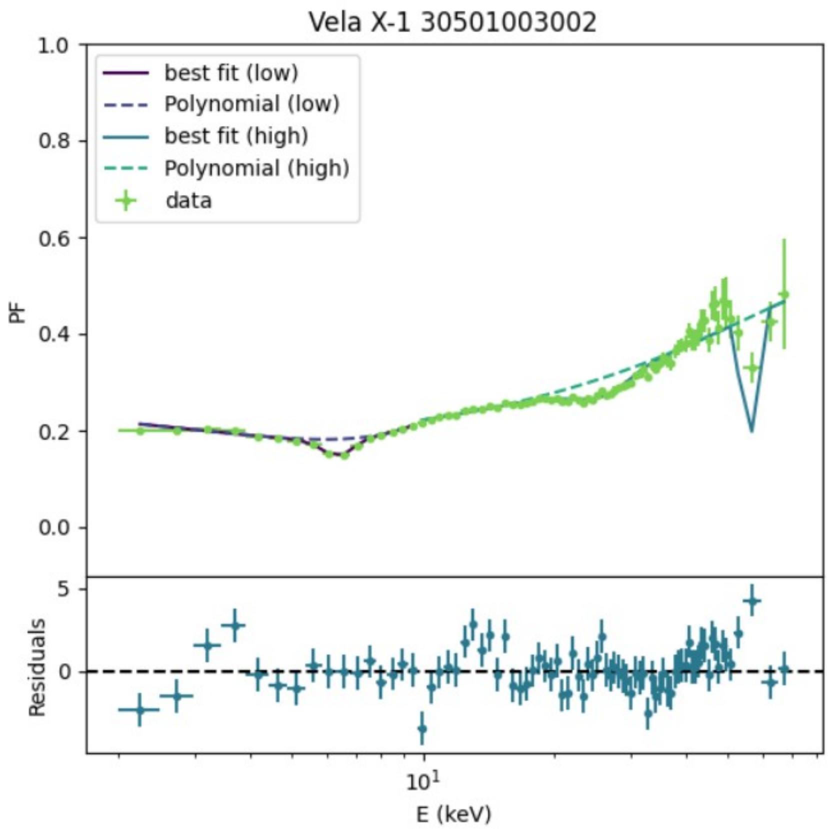
$$C_{m,i} = \frac{1}{L}(0.5A_0 + \sum_{k=1}^{i} A_k cos((2\pi t) * k + \phi_k))$$

with A_k and ϕ_k defined as follows:

$$A_k = \sqrt{X_k^2 + Y_k^2}$$

$$\phi_k = \arctan 2(\frac{Y_k}{X_k})$$

Model of the pulsed fraction



- We divide the PF spectrum in two regions, separating at 10-20 keV based on slope change.
- We see often a decrease at the Iron line energy.
- Sometimes, we see a decrease at the cyclotron line energy.
- We model this using two polynomials with as low degree as possible plus Gaussians.

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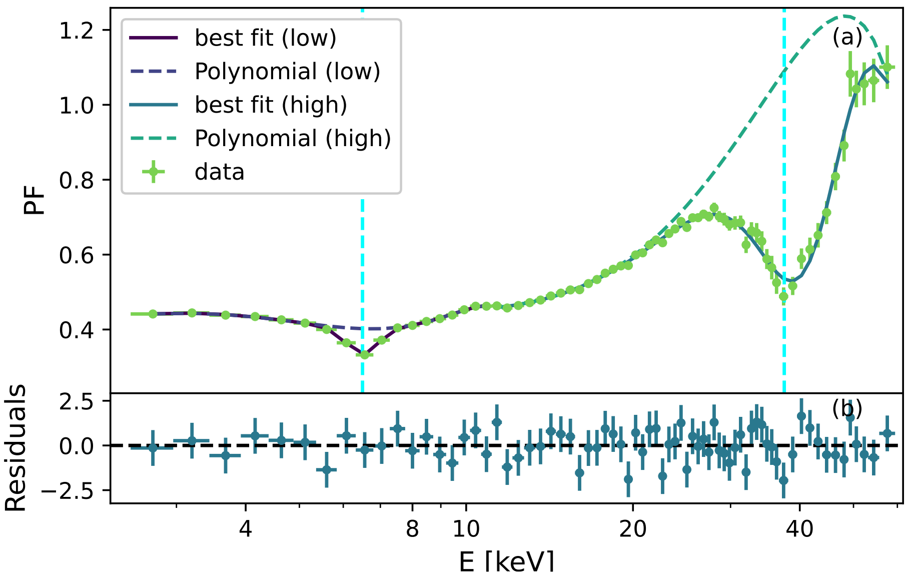

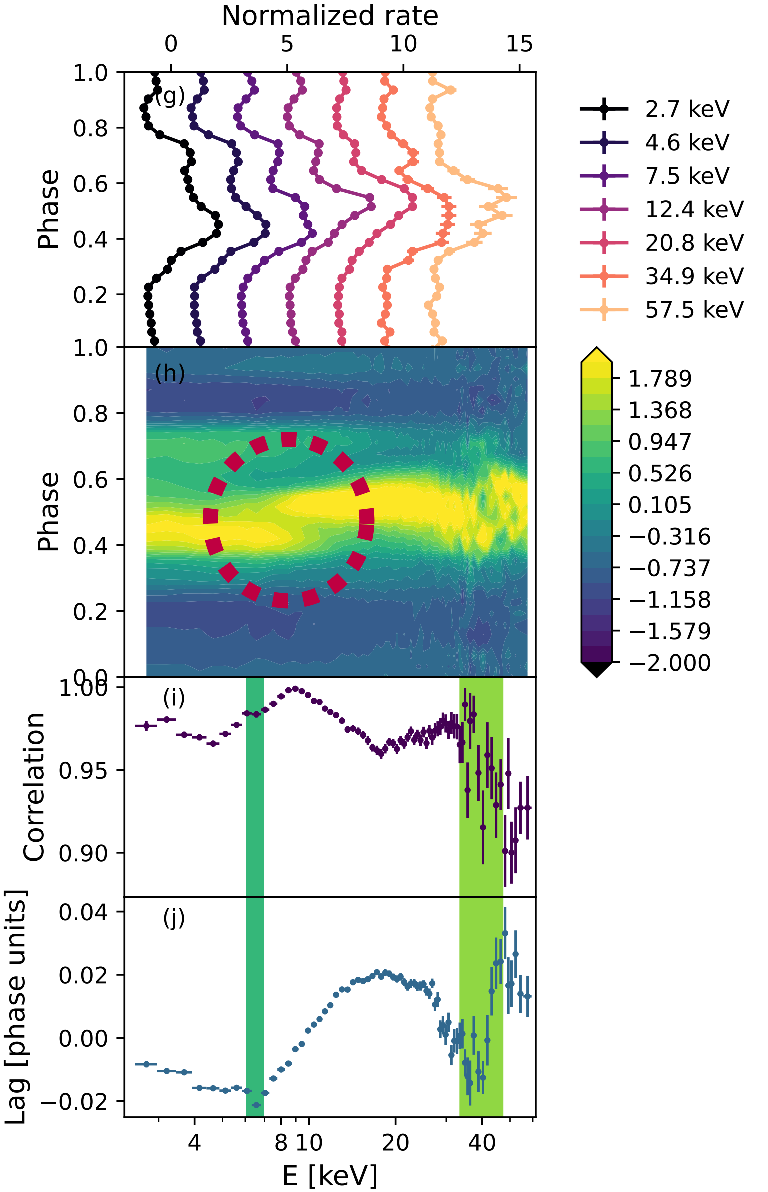

- The pulsed fraction is described by two polynomials and two negative Gaussian lines.
- Investigation of the Correlation and lag evidence a significant pulse profile
- Morphological evolution around 6-8 keV and at the cyclotron line energy.

- In future work, we will try to exploit these features to drive modeling

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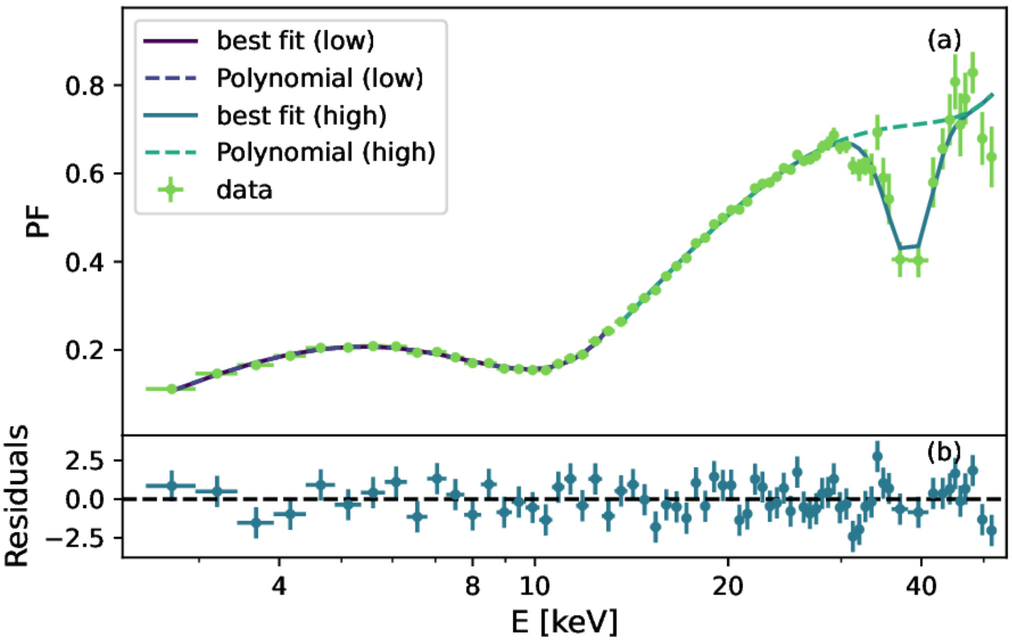

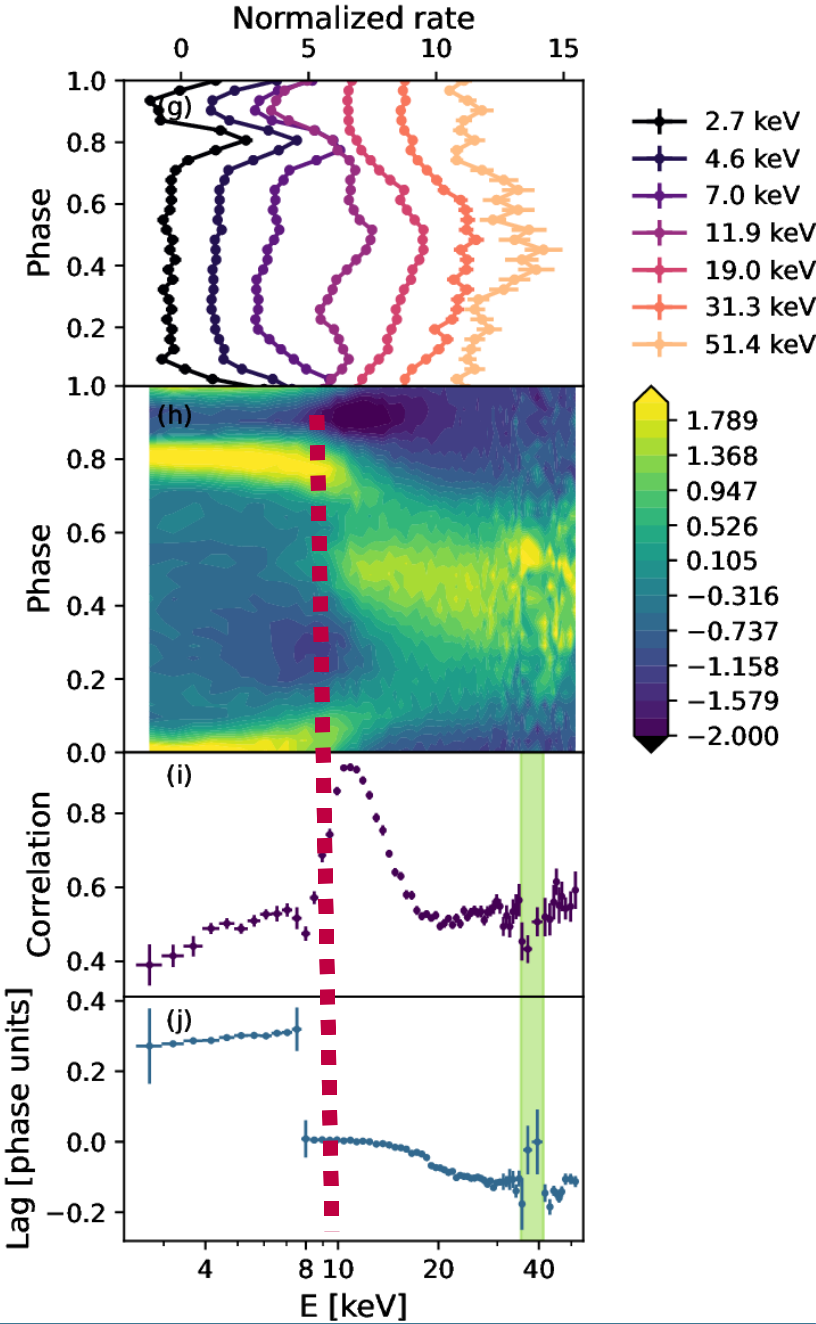

In this source:

- There is no strong Iron line
- There is a strong discontinuity in the pulse profile shape at ~9 keV:
- Different beam patterns must be present

- Do they correspond to different spectral components? (future work)

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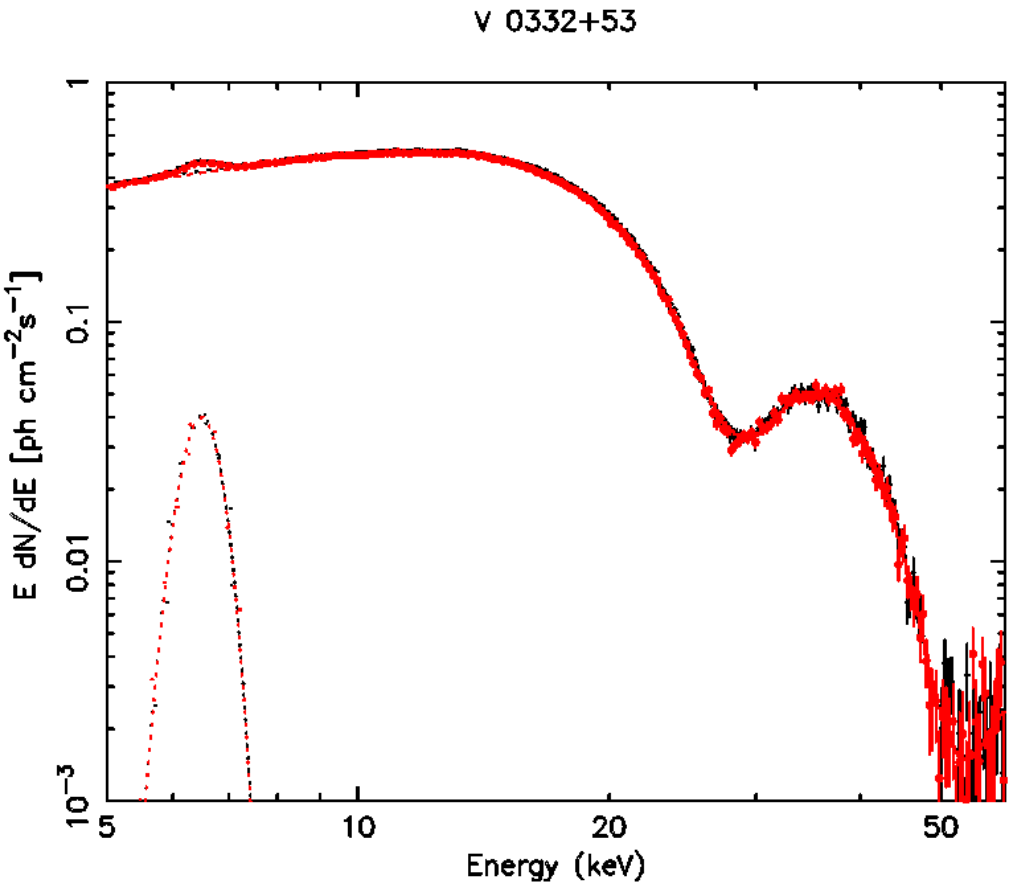

Very strong luminosity-dependent Cyclotron features at 25-27 and ~50 keV

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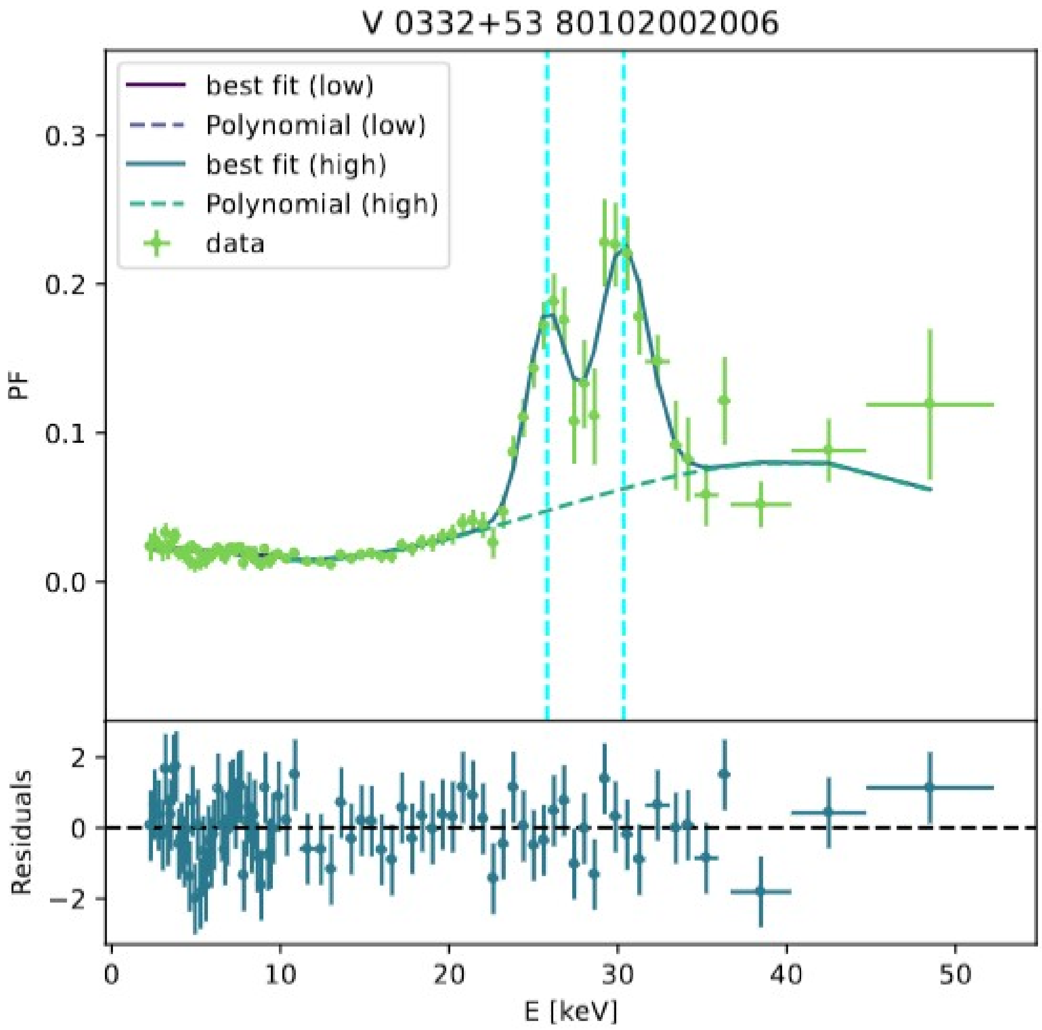
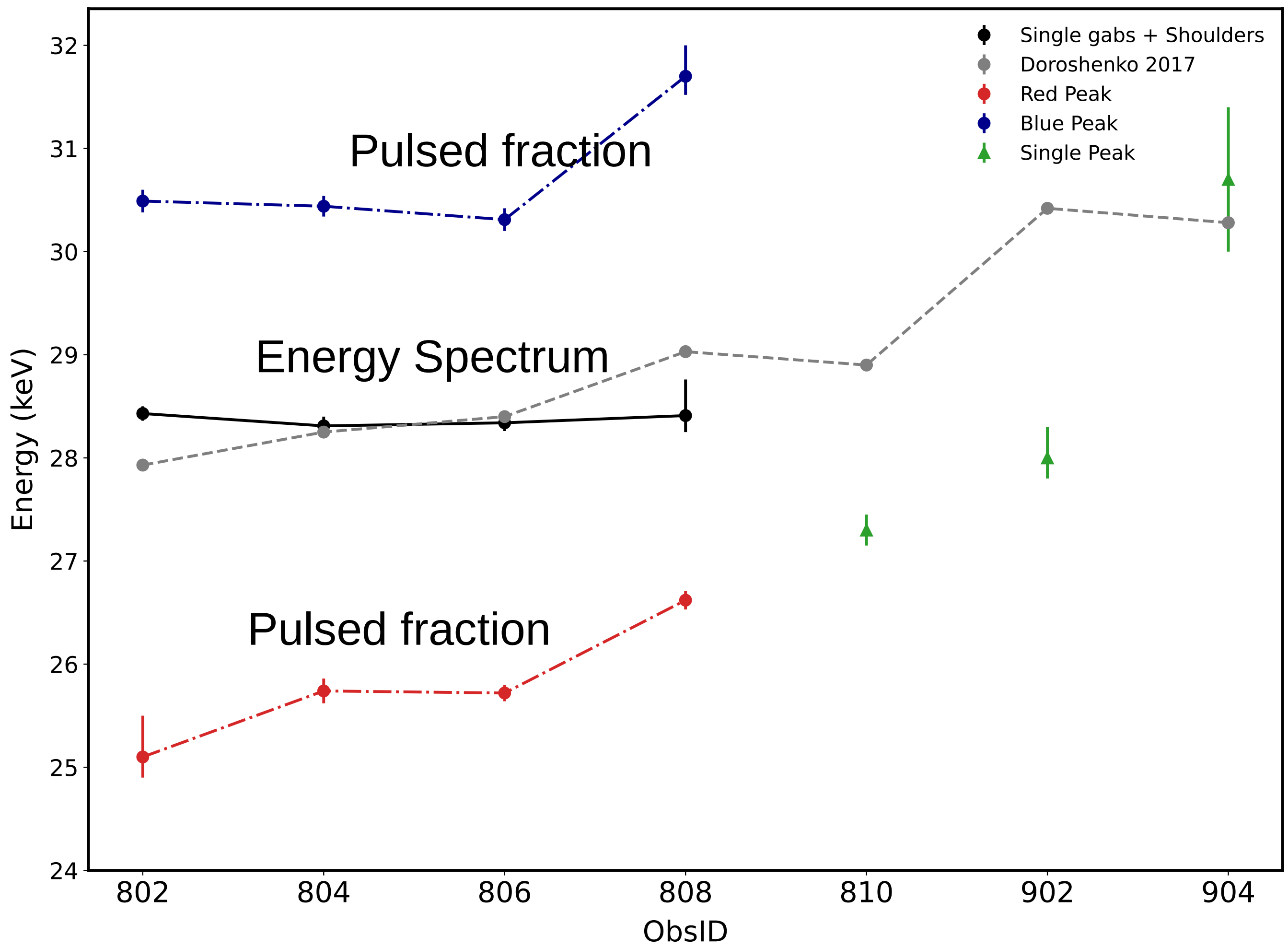


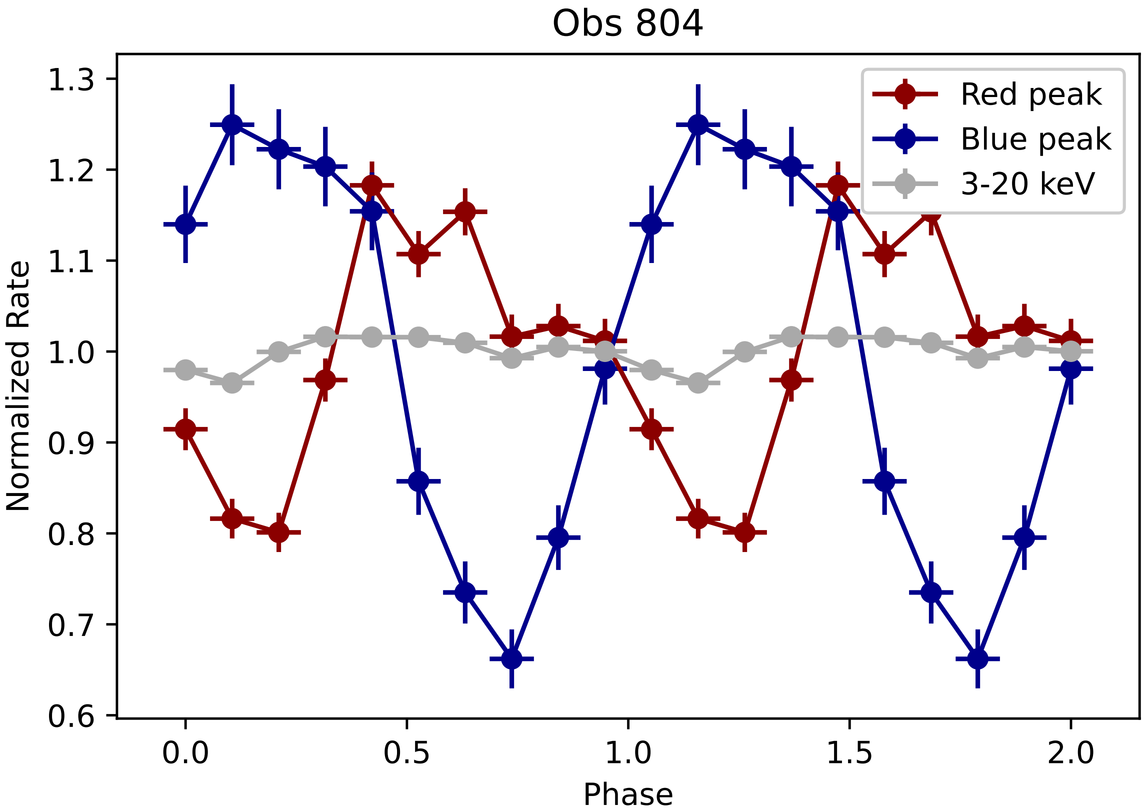
- A low pulsed fraction
- At the Cyclotron line, we find two positive Gaussians !

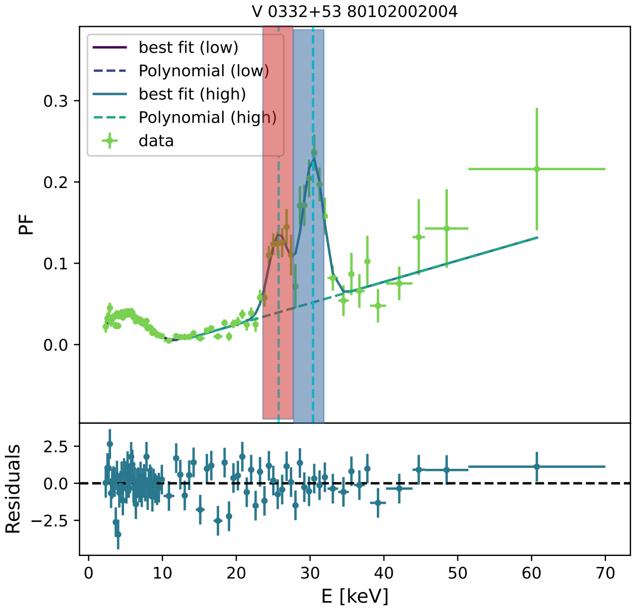
PF vs spectral



The Pulsed Fraction peaks are above and below the spectral feature

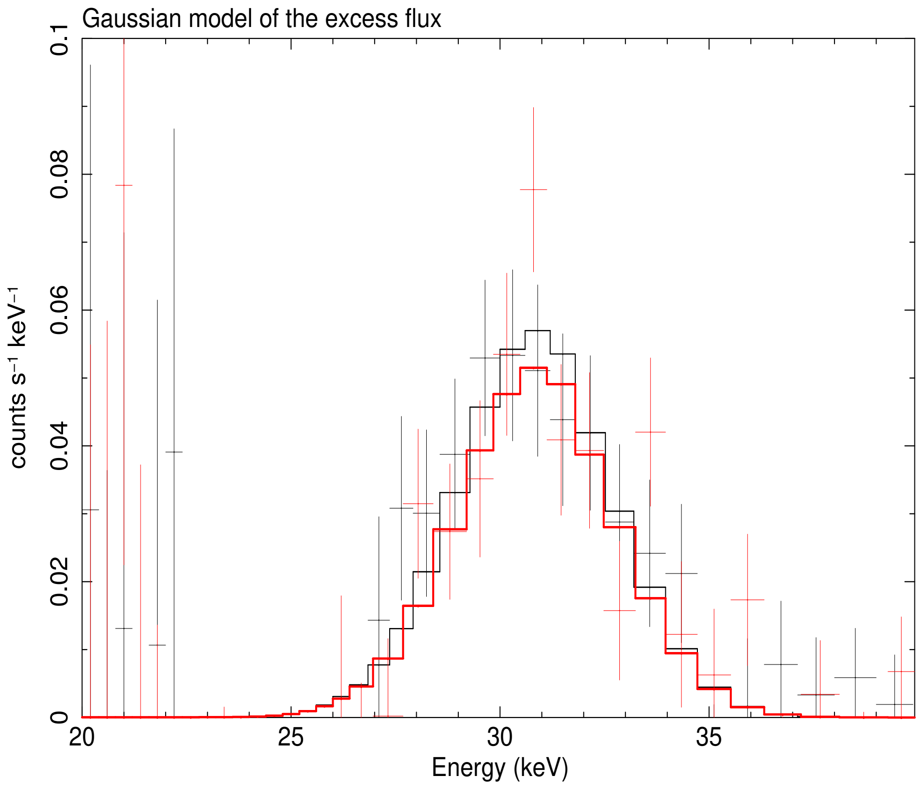
Pulses

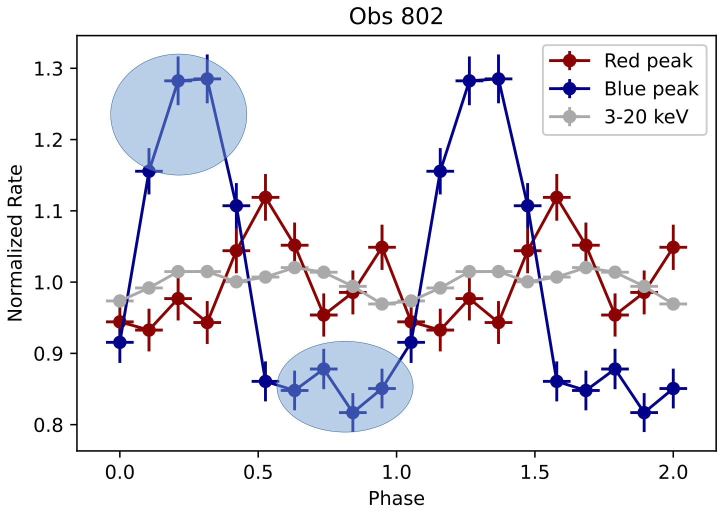




Pulses are very different at energies corresponding to the peaks in the pulsed fraction

Phase-resolved spectral analysis





- We investigate the pulsed spectrum by subtracting the spectra at the pulse peak and minimum.
- There is an excess at different energies for the red and blue peaks.

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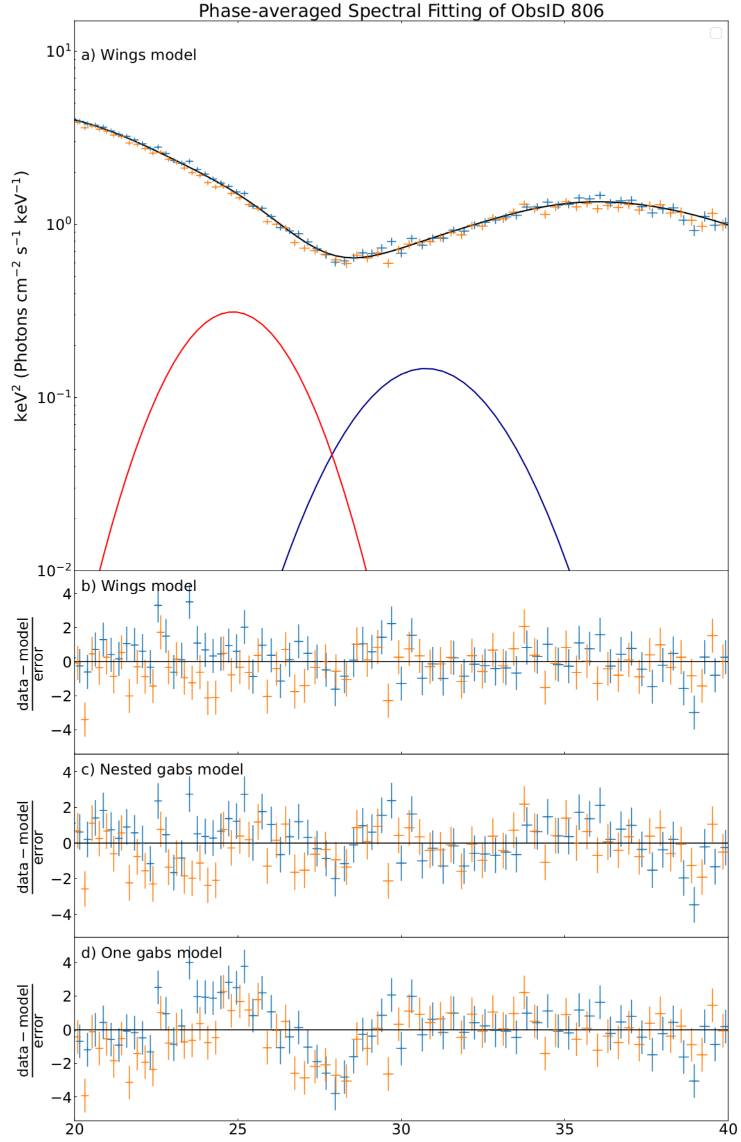
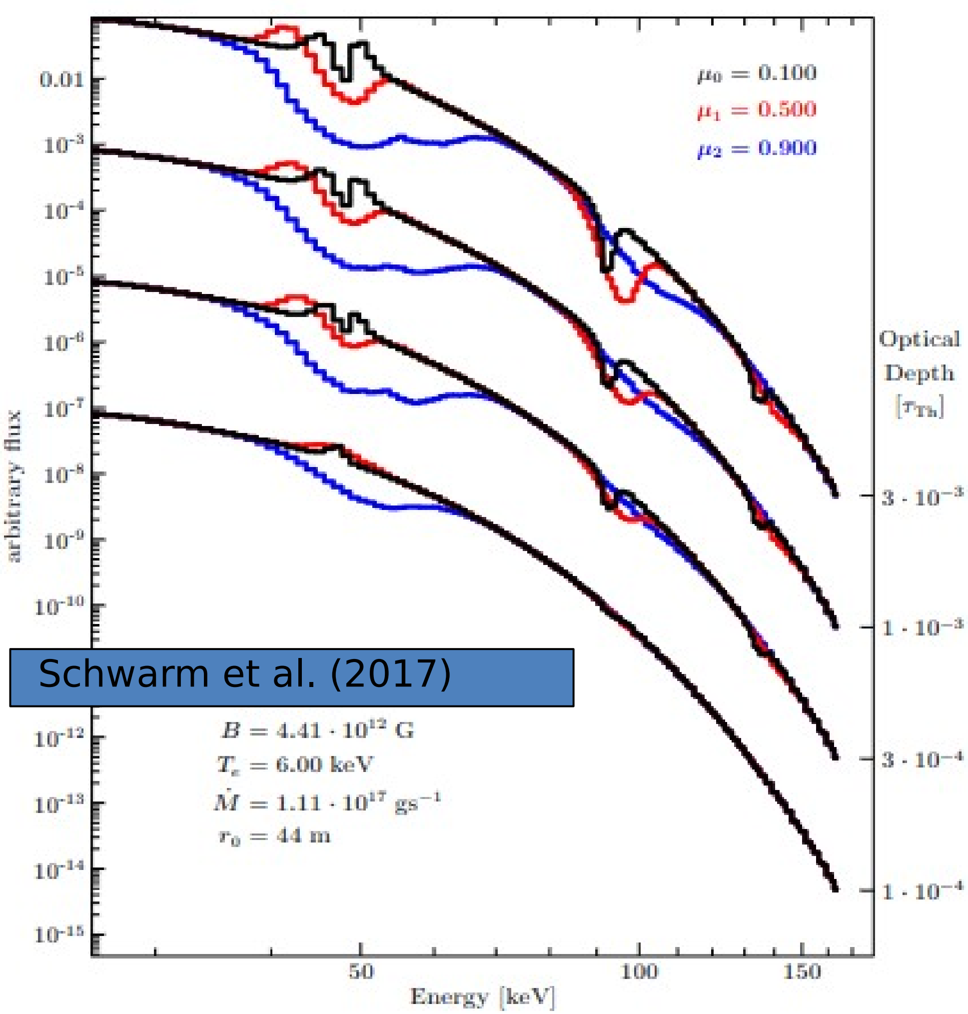
An informed model

- One Gaussian absorption provides inadequate model
- A narrower nested absorption feature was proposed, phenomelogically.
- Adding two Gaussian as "WINGS" with energy and width derived from the phase-resolved analysis is (nearly) statistically equivalent to using a nested absorption feature, but it is coherent with the pulsed fraction.



Interpretation



- Models predict the existence of shoulders due to photon spawning (recombination of higher-order scattering)
- They are not generally introduced in energy spectra, due to the need of complex modeling of the continuum
- With accurate pulsed-fraction analysis, we constrain their characteristics using Bayesian priors and manage to model shoulders as Gaussian lines.

Conclusion and Perspectives

- We developed a robust framework to obtain finely energy-resolved pulse profiles for a large sample of sources with cyclotron lines as observed by NuSTAR.
- We can derive one-dimensional reductions such as pulsed-fraction and lag-correlation spectra, we can decompose the pulses in harmonics and study the energy dependence of each normalization and phase.
- We see deficits or excesses (!) of the pulsed-fraction corresponding to the Iron lines and cyclotron scattering features.
- Sources are very diverse and we are focusing on some interesting cases to drive the spectral modeling.